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Working paper

Translating global warming targets of the Paris Agreement into globally consistent objectives for national GHG emission reductions. A GHG emissions budget approach.

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Abstract

This working paper addresses the problem of preserving consistency of national or regional greenhouse gas (GHG) emission reduction pathways with the global warming targets stipulated by the Paris Agreement. We propose a method of deriving robust, physically grounded and globally consistent limits of cumulative GHG emissions and corresponding reference reduction pathways for both the 1.5 °C and the 2°C warming target, against which national/regional GHG emission pathways can be compared. This derivation builds on the study by Jonas *et al.* (2014) and its update Jonas & Żebrowski (2016) and is based on the recently updated estimates of carbon budgets for 1.5 °C and 2°C warming targets presented in the IPCC's special report on a global warming of 1.5 °C (Rogelj *et al.* 2018).

This working paper (i) presents our method together with a concise physical background; and (ii) demonstrates how consistency with global warming targets can be assessed for scenarios of green transformation for the economies of a large region (EU) and a small country (Austria).

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1. Introduction

The goal of the Paris Agreement adopted by the international community is to limit global warming to well below 2 °C above the pre-industrial level, with the ambition to limit it to 1.5 °C (UNFCCC 2015). The envisioned mechanism for achieving this goal is a bottom-up collective action of all countries, which are expected to reduce their emissions in accordance with their nationally determined contributions (NDCs). This poses a double challenge for national policymakers tasked with designing economic and environmental policies aiming at reducing greenhouse gas (GHG) emissions of their countries in line with the goals of the Paris Agreement. First, they need to understand how the long-term target of keeping the global warming below 2 °C (and ideally below 1.5 °C) in 2100 and beyond translates into constraints on national GHG emissions in mid-term (e.g., by 2050) and in what range their NDCs should be to meaningfully contribute to mitigation efforts of international community. Secondly, they need to ensure that their policies are not only economically viable but also result in pathways of national GHG emissions that are consistent with the goals of the Paris Agreement.

Designing NDCs and national climate policies without proper care for the global context can seriously undermine their stated goals. Climate change is a planetary-scale process unfolding over centennial timescales and driven mainly by the global anthropogenic GHG emissions. It is thus impossible to establish a one-to-one relationship between a pathway of national GHG emissions (in mid-term) and the future stabilization of the global mean surface temperature (GMST) (several decades down the line). Indeed, without a global context, the same trajectory of national emissions may contribute to different global GHG emission pathways that will result in different levels of warming. Moreover, different national policies may underlie the same trajectory of domestic emissions while they may differently affect the global economy and indirectly influence emissions of other countries[1], making it still more difficult to appraise the expected effect of bottom-up, uncoordinated national climate policies.

A possible way of ensuring that a trajectory of national GHG emission is in line with a given warming target (e.g., target of the Paris Agreement) is to embed it within a global climate change mitigation scenario, the effect of which on the GMST increase has been assessed. Such studies are available in literature. For instance, the IPCC's "Global warming of 1.5C" special report (Rogelj *et al*. 2018) reviews an ensemble of scenarios developed with use of various integrated assessment models (IAMs) and feeds the resulting scenarios' GHG emission pathways into medium-complexity climate models to assess their corresponding GMST response. Yet, although feasible, embedding a national emissions-reduction scenario within a global one is a tedious exercise with several serious methodological drawbacks. First, adopting a global scenario to a regional context requires additional assumptions and thus multiplies uncertainties. Secondly, relying on storylines of existing scenarios limits the space for exploring new visions of radical economic transformations that developed economies need to undergo in order to reach the warming target of the Paris Agreement. Indeed, it is recognized that IAMs struggle to model rapid economic and institutional changes driven by disruptive technologies (see e.g., Forster *et al*. 2018, section 2.SM.1.2).

With this paper we aim at bridging the gap between: detailed models of national or regional economies encompassing natural resources and GHG emissions, which can serve as agile tools of a bottom-up climate

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[1] E.g., introducing low-emission technologies in domestic production genuinely reduce both global and national GHG emissions while off-shoring of carbon-intensive production to other countries does not.

policy design allowing for identification of economically viable scenarios of GHG emission reductions[2] but which are not rigorously anchored in the global context; and an internally fully consistent but rigid and resource-intensive top-down integrated modeling at a global scale, which, however, lacks a region-specific details relevant to national climate policy design. To this end we propose a method of deriving robust budgets of cumulative national GHG emissions and corresponding reference emission pathways that are in line with the warming targets of 1.5 °C and 2 °C of the Paris Agreement, and which benefits from the internal consistency of global-scale top-down climate models without limiting agility of locally specific models.

Our method builds on the study of Jonas *et al.* (2014) and its extension Jonas & Żebrowski (2016). It is based on the concept of a budget of global cumulative GHG emissions that keeps the increase of GMST below a specified level with a predefined probability. In Section 2 we introduce the scientific basis for the concept of carbon budget, discuss its extension to include also non-CO_2 GHGs, describe derivation of the global budgets of aggregated GHG emissions for the 1.5 °C and 2 °C warming targets and outline their uncertainty ranges. We also derive reference pathways for global GHG emissions that satisfy the corresponding emission budget constraints. In Section 3 we describe how these global constraints can be translated into a set of globally consistent constraints for emissions of all nations. We also explain how to scale them in time to find targets of national GHG emission reduction policies in the medium term, e.g., in 2050. As a case example we present cumulative emissions budgets and corresponding reference emission pathways for a large economic bloc of EU as well as for a small open economy of Austria. We also demonstrate how these budgets can be used to assess the alignment of regional and national scenarios of economic transformation with the targets of the Paris Agreement. In Section 4 we summarize our results and discuss contexts in which our methodology can aid modeling and formulation of national and regional climate policies.

2. Global GHG emission budgets

2.1. Scientific basis for deriving carbon budgets and their uncertainties

Determining the contribution of anthropogenic GHG emissions to the increase of GMST[3] requires a detailed understanding of: (1) how anthropogenic emissions of CO_2 and other greenhouse gases interfere with cycling of these gases in the earth system, what fraction of these emissions is absorbed by the terrestrial sinks and how GHG concentrations in the atmosphere build up over time; (2) what radiative forcing is caused by the presence of GHGs in the atmosphere and what energy imbalance does it cause; and (3) how this energy flux translates into the increase of GMST. Although our understanding of these processes has improved considerably in recent years and decades, substantial uncertainties remain for each of these steps, and they compound when translating anthropogenic GHG emissions to GHG concentrations to GMST increase.

Nevertheless, a robust linear relationship between the cumulative anthropogenic CO_2 emissions and the increase of GMST from the pre-industrial level (1850-1900 average) has been observed in the historical data.

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[2] A prominent example is the integrated assessment framework linking PRIMES, GAINS and GLOBIOM models that was used in a study commissioned by the European Commission to explore EU-wide scenarios of transformation towards a green economy (EC, 2018) and which are discussed in Section 3.

[3] Estimated global average of near-surface air temperatures over land and sea-ice, and sea surface temperature over the ice-free regions.

The best estimate of the transient climate response to cumulative emissions (TCRE) is an increase of 0.45 °C of GMST per 1000 Gt CO_2 with a 33-67% uncertainty range of [0.35 °C – 0.55 °C] - see Fig. 1 with further details in Forster *et al.* (2018, section 2.SM.1.1.2.1). Moreover, modelling experiments indicate that this relationship is to a large extent independent of the actual shape of the future CO_2 emissions pathway (as long as it doesn't exhibit radical breaks) and can be extrapolated with a manageable level of uncertainty for cumulative emissions within a range up to 6000 Gt CO_2 (Rogelj *et al.* 2018, section 2.2.2).

The linear relationship between the cumulative CO_2 emissions and the increase of global surface temperature can be used to calculate the carbon budget that allows to keep the global warming below a specified threshold with a predefined probability. In this report we will focus on carbon budgets that will ensure meeting 1.5 °C and 2 °C with 50% probability (although, we will consider also other probability levels to explore the uncertainty of these carbon budgets).

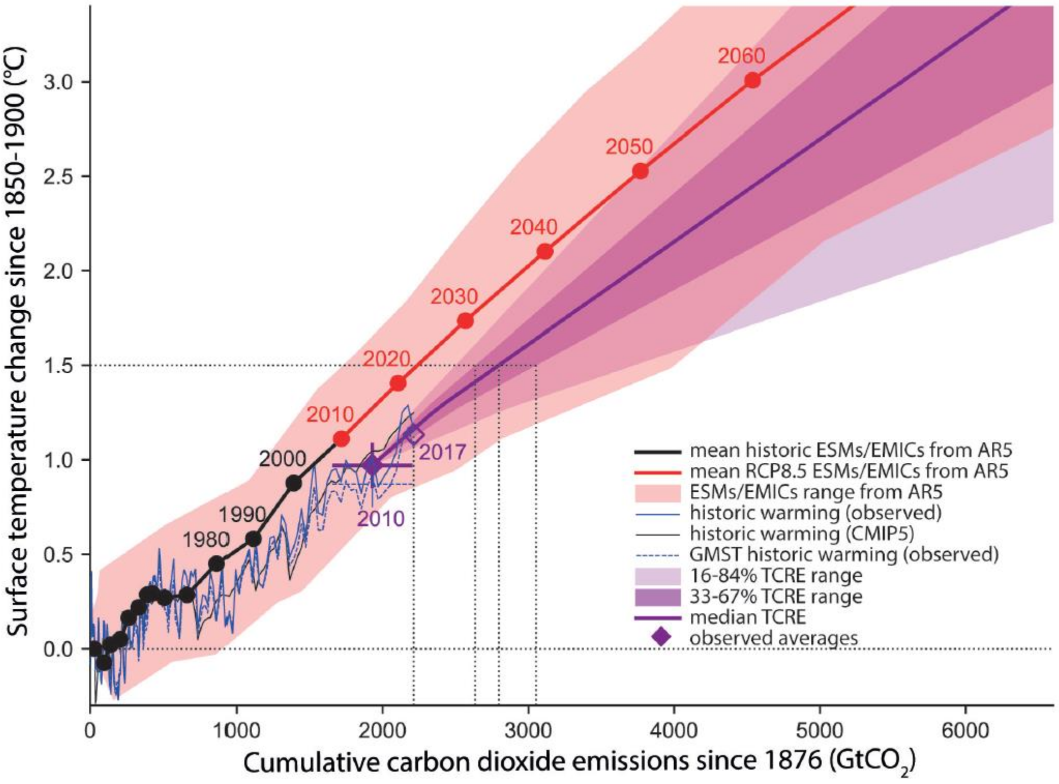

***Figure 1**: Temperature changes relative to 1850-1900 average versus cumulative CO2 emissions since 1876. The near linear relationship is a basis for the TCRE calculations. (Source: Rogelj et al. (2018), p. 105, Figure 2.3).*

The first step in deriving a carbon budget is to specify how much additional warming is allowed, which requires selecting a warming target, as well as choosing a reference allowing to calculate the level of warming that already took place since the pre-industrial era. The IPCC defines the current level of warming as the 2006-2015 average of GMST, which is estimated to be 0.87 °C ±0.12 °C. However, the reduced-complexity climate models which are used to assess the warming effect of future GHG emissions pathways use the global mean surface air temperature[4] (GSAT) instead. The 2006-2015 GSAT average is estimated to be 0.97 °C ±0.1 °C.

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[4] Global average of near-surface air temperatures over land and oceans.

Taking GSAT as a reference the allowed temperature increases for the 1.5 °C and 2 °C targets are 0.53 °C and 1.03 °C, respectively.

As a reference for the derivation of carbon budgets we choose 2010, that is the middle of the time interval 2006-2015 over which the current level of warming (GSAT average) is calculated. To derive a carbon budget $B(\Delta T)$ that gives a p% chance[5] of keeping the increase of global surface temperature below the chosen limit ΔT we use the following identity:

$$TCRE_p = \frac{\Delta T}{B(\Delta T)}$$

where $TCRE_p$ denotes the p-th percentile of TCRE estimate range based on multiple models' runs (see IPCC, 2014). To calculate carbon budgets as of 2018 we subtract from B the 2011-2017 anthropogenic CO_2 emissions, estimated to be 290 Gt CO_2 (Le Quéré *et al.* 2018). The results are gathered in Table 1.

***Table 1**: Carbon budgets (CO_2 only) as of 2018 calculated for 1.5 °C and 2 °C warming targets.*

Warming target	ΔT	Carbon budget as of 2018 [Gt CO_2]		
		67th percentile TCRE [0.55 °C per 1000 Gt CO_2]	50th percentile TCRE [0.45 °C per 1000 Gt CO_2]	33rd percentile TCRE [0.35 °C per 1000 Gt CO_2]
1.5 °C	0.53 °C	670	890	1220
2 °C	1.03 °C	1580	2000	2650

Table 1 reflects uncertainties of 1.5 °C and 2 °C carbon budgets due to uncertain estimates of TCRE. It is compounded by uncertainties in both estimates of current level of warming and in accounting of historical CO_2 emissions (see Rogelj *et al.* 2018, section 2.2.2.2 for further details). Another serious source of uncertainty stems from the response of the Earth climate system to continued anthropogenic CO_2 emissions. No significant Earth system feedbacks were detected in historical observations and models used to assess TCRE do not account for such feedbacks. Yet, feedbacks like CO_2 and CH_4 released by thawing permafrost or wetlands are expected in the future and are estimated to be in the order of 100 Gt CO_2 until the end of this century, with further feedbacks expected after 2100. Moreover, the linear relationship between cumulative CO_2 emissions and temperature increase critically depends on terrestrial and oceanic CO_2 sinks to continue absorbing approximately half of the anthropogenic CO_2 emissions (see Fig 2). If the strength of natural sinks falters or collapses – as may be the case with Amazon rainforests (Hubau *et al.* 2020) – the available carbon budget would be significantly smaller.

2.2. Contribution of non-CO_2 gases

The TCRE-based carbon budgets presented in Table 1 refer only to cumulative anthropogenic CO_2 emissions and would ensure meeting the specified warming targets only in the absence of other climate forcing. In reality, however, anthropogenic emissions of non-CO_2 greenhouse gases contribute significantly to the global warming (approximately 20% of anthropogenic climate forcing) and thus carbon budgets need to be corrected to offset these contributions.

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[5] This should be treated more as a qualitative statement expressing our confidence based upon multiple modelling experiments, rather than proper quantitative estimate of probability of not exceeding the warming target.

Non-CO_2 GHGs influence the global energy balance on various time scales. The main long-lived GHG other than CO_2 is the nitrous oxide (N_2O), which stays in the atmosphere for about 100 years. Around three quarters of N_2O emissions comes from fertiliser use in agriculture. Agriculture is also the main source of methane (CH_4) which is the most important short-lived GHG. It lasts in the atmosphere for about a decade but has a significant global warming potential and is a precursor to ozone, which itself is a GHG. Other, less abundant short-lived GHGs are the fluorine gases, aerosols, and aerosol- and ozone-precursors.

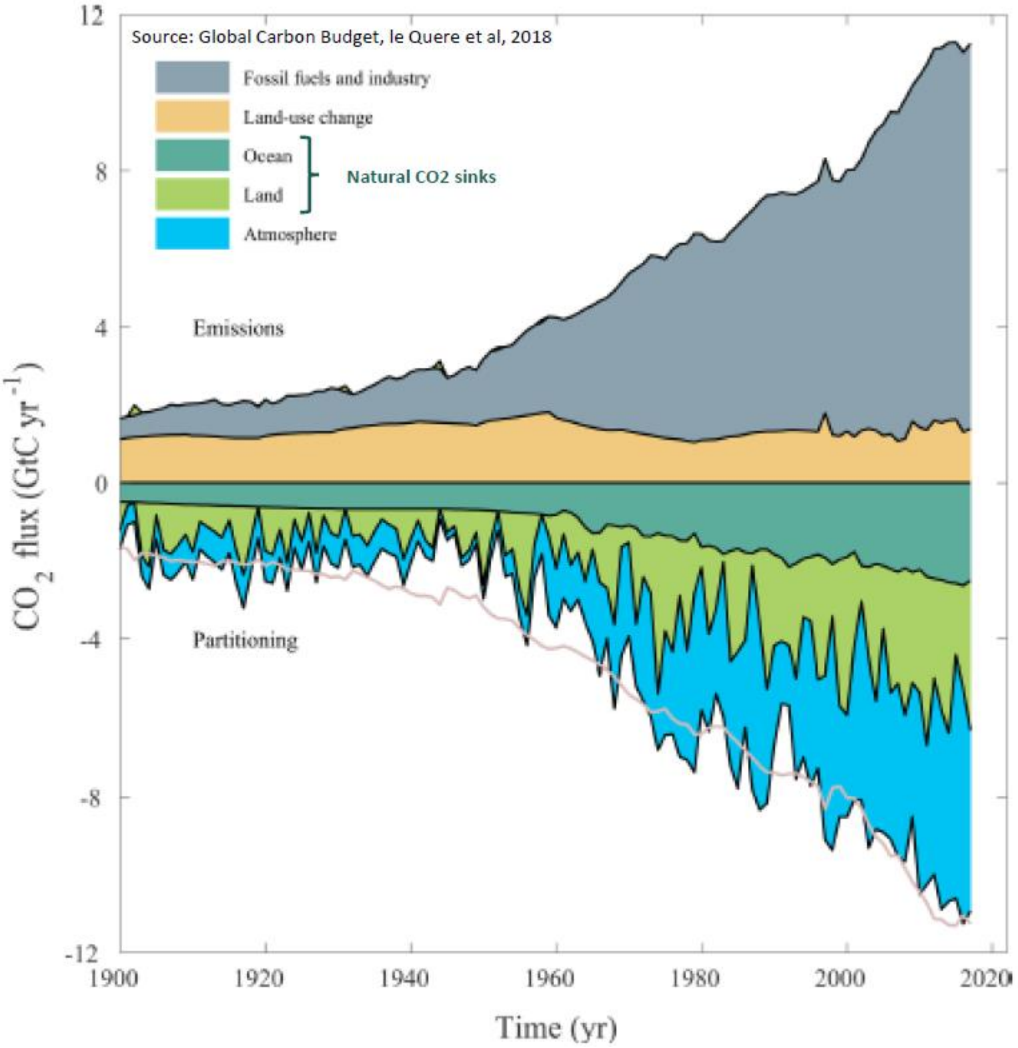

***Figure 2**: Combined components of the global carbon budget over time (Source: Le Quéré et al. (2018), Fig. 3)*

While the increase in global mean temperature caused by the long-lived GHGs is well predicted by their cumulative emissions, the contribution of short-lived greenhouse gases to the global warming strongly depends on the shape of the actual emissions pathway. Therefore, determining the contribution of non-CO_2 GHGs to the global temperature increase needs to be based on the analysis of integrated pathways of all major greenhouse gases.

The IPCC's SR15 report (Rogelj *et al.* 2018) bases its assessment of the contribution of non-CO_2 gases to the global temperature increase on the analysis of over 200 climate change mitigation scenarios developed with various integrated assessment models. GHG emission pathways for these scenarios (consisting of yearly emissions of anthropogenic GHG broken down by type of gas) were plugged into reduced complexity climate models (FAIR and MAGICC) to assess the resulting evolution of GSAT within the time horizon of 2100. It was discovered that aggressive reductions of non-CO_2 emissions, particularly of CH_4, in the first half of the 21st century help to slow down global warming in the short term and are essential to stabilising the increase of GSAT at or below 2 °C by 2100. The peak of non-CO_2 radiative forcing is expected approximately at the same time when net zero CO_2 emissions will have to be reached. Hence it is possible to calculate by how much the CO_2-only budgets will have to be reduced to offset the non-CO_2 contribution to the increase of GSAT. First, for each scenario a peak temperature increase (caused by all anthropogenic GHGs) relative to its 2006-2015 average is calculated, together with the corresponding warming due to non-CO_2 radiative forcing at the time of zero net CO_2 emissions. Next, the reference non-CO_2 temperature contribution (RNCTC) is calculated as a median line in the quantile regression of non-CO_2 warming contribution vs. peak temperature increase – see Figure 3. The RNCTC for the 1.5 °C target (i.e. 0.53 °C of allowed temperature increase) is estimated to be 0.14 °C at the time of zero net CO_2 emissions. For a 2 °C warming target (0.93 °C of allowed temperature increase) the RNCTC is 0.23 °C. For a given target temperature increase ΔT the budget $B_{adj}(\Delta T)$ of CO_2 emissions adjusted for the contribution of non-CO_2 GHG can be calculated using the identity

$$TCRE_p = \frac{\Delta T - RNCTC_p(\Delta T)}{B_{adj}(\Delta T)}$$

where $TCRE_p$ stands for p-th percentile of TCRE and $RNCTC_p(\Delta T)$ denotes the p-th percentile of RNCTC for temperature increase ΔT. Table 2 gathers the reductions to CO_2-only TCRE-based budgets needed to offset the contribution of non-CO_2 GHGs as well as adjusted carbon budgets.

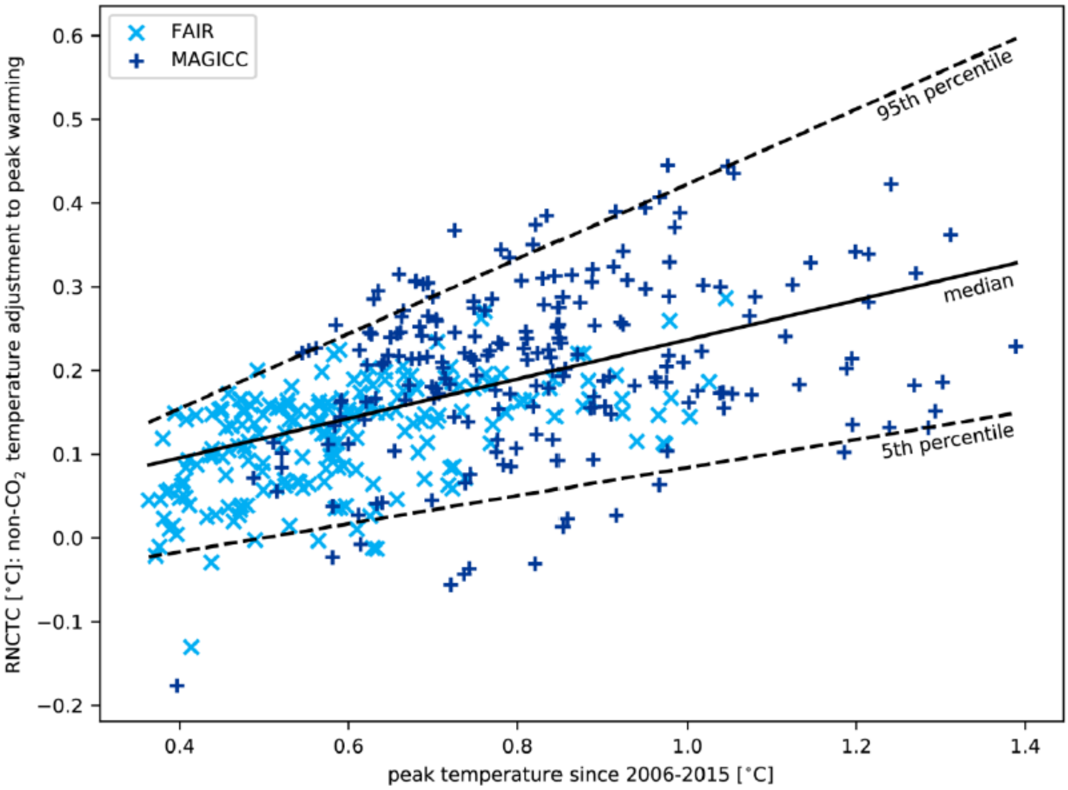

***Figure 3**: Relationship of RNCTC with peak temperature in the FAIR and MAGICC models. The black line is the linear regression relationship between peak temperature and RNCTC. The dashed lines show the quantile regressions at the 5th and 95th percentile. (Source: Forster et al. (2018), Fig. 2.SM.4)*

***Table 2**: Adjusted carbon budgets (CO_2 only) as of 2018 calculated for 1.5 °C and 2 °C warming targets. They are derived from median TCRE carbon budgets presented in Tab. 1, by subtracting the amount of cumulative CO_2 emissions required to offset the non-CO_2 climate forcing. (Source: Rogelj et al. (2018)).*

Warming target	ΔT	Adjusted carbon budget as of 2018 [Gt CO_2]	Offset to balance non-CO_2 climate forcers [Gt CO_2]
1.5 °C	0.53 °C	580 [420 – 840]	310 [260 – 390]
2 °C	1.03 °C	1500 [1170 – 2030]	500 [430 – 630]

2.3. Reference global emissions pathways for 1.5 °C and 2 °C warming targets

We use the adjusted CO_2 budgets to derive reference pathways of anthropogenic CO_2 emissions for 1.5 °C and 2 °C warming targets. Since the variation in shape of CO_2 emission pathways has little effect on the resulting global temperature increase under the condition that cumulative emissions do not change, we chose a simplified shape for the reference pathway for anthropogenic CO_2 emissions. Namely, we assume constant rate (linear) reductions of net anthropogenic CO_2 emissions from 2017 onward to reach (net) zero emissions when cumulative emissions (the area under the pathway) equal the adjusted CO_2 budget, i.e.

$$\frac{1}{2}E_{net\ CO2}(2017) \times \tau_{ZN}(\Delta T) = B_{adj}(\Delta T)$$

where $E_{net\ CO2}(2017)$ and $\tau_{ZN}(\Delta T)$, respectively, denote net anthropogenic CO_2 emissions in 2017 and the time of reaching zero net CO_2 emissions corresponding to the warming target ΔT. Moreover, we assume that after $\tau_{ZN}(\Delta T)$ the pathway continues the linear decrease along the same slope $a = -E_{net\ CO2}(2017)/\tau_{ZN}(\Delta T)$ until time $\tau_L(\Delta T)$ when it levels out at negative CO_2 emissions E_C, which are necessary to compensate for the climate forcing due to non-CO_2 emissions after $\tau_{ZN}(\Delta T)$. More precisely, we demand that the CO_2 removed from atmosphere must balance the cumulative non-CO_2 emissions between $\tau_{ZN}(\Delta T)$ and 2100. Thus, $\tau_L(\Delta T)$ and E_C can be computed by solving the set of equations

$$\begin{cases} \frac{1}{2}(\tau_L - \tau_{ZN})E_C + (2100 - \tau_L)E_C = -CE_{nonCO2} \\ E_C = (\tau_L - \tau_{ZN})a \end{cases}$$

where a is the slope of the pathway and CE_{nonCO2} stands for cumulative non-CO_2 emissions between τ_{ZN} and 2100.

At this point we need assumptions on the evolution of non-CO_2 GHG emissions. It is important to remember that non-CO_2 climate forcing depends on the timing of non-CO_2 emissions (particularly on that of the short-living methane). The adjusted carbon budgets were derived under specific assumptions about the shape of non-CO_2 emission pathways. Moreover, we need to know cumulative non-CO_2 emissions from the time of zero net CO_2 emissions and the end of the 21st century[6].

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[6] Under all scenarios considered in SR15 the CH_4 emissions stabilize in the second half of the 21st century. Constant methane emissions and the fact that N_2O is a long-lived GHG imply that cumulative non-CO_2 emissions are a good predictor of the non-CO_2 climate forcing over that period.

To be consistent with the method of calculating the adjusted carbon budget used in SR15 (and presented in section 2.2. and 2.3. of this report) we base our simplified reference non-CO_2 emission pathways for the warming targets of 1.5 °C and 2 °C on the benchmark methane and nitrous oxide emissions for the "1.5 °C low OS" and "Higher 2 °C" classes of pathways used in SR15[7]. The "1.5 °C low OS" class contains pathways which limit the warming to below 1.5 °C in 2100 with a 50-67% probability of overshooting this level of warming temporarily at some point during the 21st century; while the "Higher 2 °C" class consists of pathways limiting warming to below 2 °C during the entire 21st century (Rogelj *et al.* 2018, p. 100, Table 2.1). We choose these two categories of pathways because their definitions coincide best with the notion of 50th-percentile adjusted carbon budgets for the warming targets of 1.5 °C and 2 °C. The benchmark CH_4 and N_2O emissions are gathered in Tables 3 and 4, respectively, and our simplified reference non-CO_2 emission pathways are based on linear interpolations between these benchmark points.

Table 3*: Benchmark methane emissions based on median emissions for classes "1.5 °C low OS" and "Higher 2 °C" as presented on Figure 2.7. (a), SR15, Ch. 2, p. 120. We assume that emissions in 2020 are 380 Mt CH_4, which are slightly higher than 2010 emissions indicated on the aforementioned figure and is well within the range of uncertainty spanned by different estimates of current global CH_4 emissions[8]. Moreover, we assume that from 2050 on global methane emissions are constant.*

Methane emissions		2020 [Mt CH_4]	2030 [Mt CH_4]	2050 [Mt CH_4]	2100 [Mt CH_4]
1.5 °C low OS		380	240	170	170
Higher 2 °C		380	270	200	200

Table 4*: Benchmark nitrous oxide emissions based on median emissions for classes "1.5 °C low OS" and "Higher 2 °C" as presented on Figure 2.6. (d), SR15, Ch. 2, p. 117.*

Nitrous oxide emissions	2020 [Mt N_2O]	2030 [Mt N_2O]	2050 [Mt N_2O]	2100 [Mt N_2O]
1.5 °C low OS	10.5	8.5	7.5	6.5
Higher 2 °C	10.5	9.5	8	7

The only non-CO_2 greenhouse gases considered here are CH_4 and N_2O, since they are responsible for approximately 98% of non-CO_2 climate forcing. Thus, the above assumptions on the evolution of methane and nitrous oxide allow us to fully specify the reference CO_2 and total GHG pathways for the global warming targets of 1.5 °C and 2 °C, displayed in Figures 4 and 5, respectively. The characteristics of these pathways are summarized in Table 5.

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[7] Benchmark emissions are taken to be median emissions over emissions scenarios within the class of emission pathways.

[8] See EPA projections: https://cfpub.epa.gov/ghgdata/nonco2/ and Global Methane Budget https://www.globalcarbonproject.org/methanebudget/

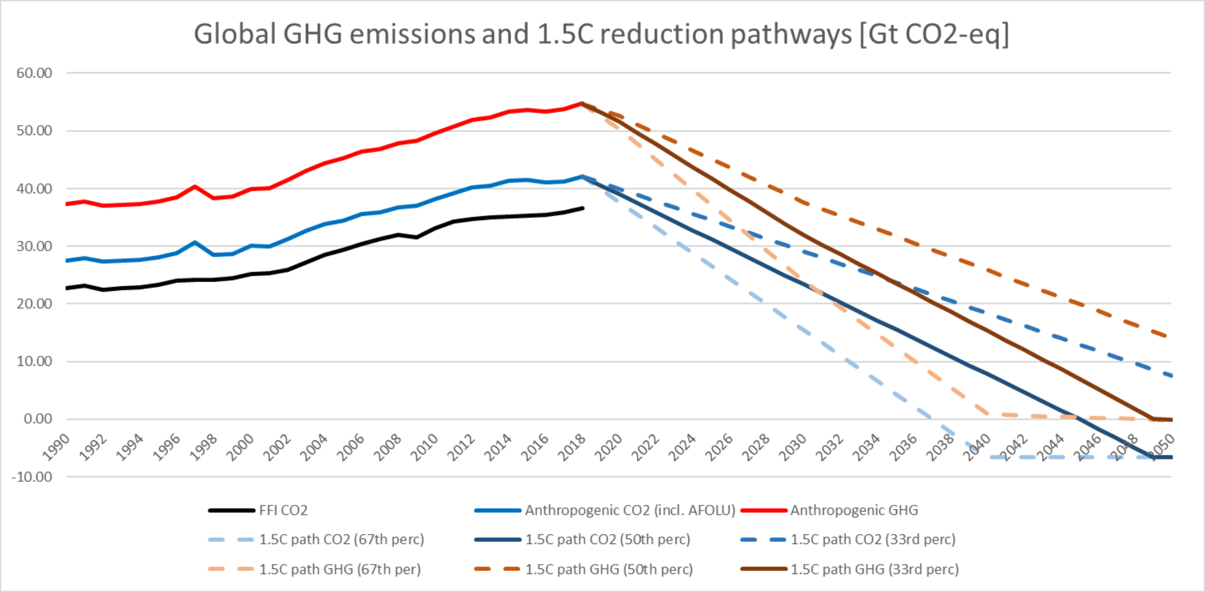

Figure 4: *Historical emissions of anthropogenic GHG (CO_2 from fossil fuel burning and industry, net anthropogenic CO_2 and aggregated GHGs) and reference pathways of net CO_2 and aggregated GHG emissions for 1.5 °C target. Dashed lines indicate uncertainty ranges due to uncertainty of adjusted CO_2 budget.*

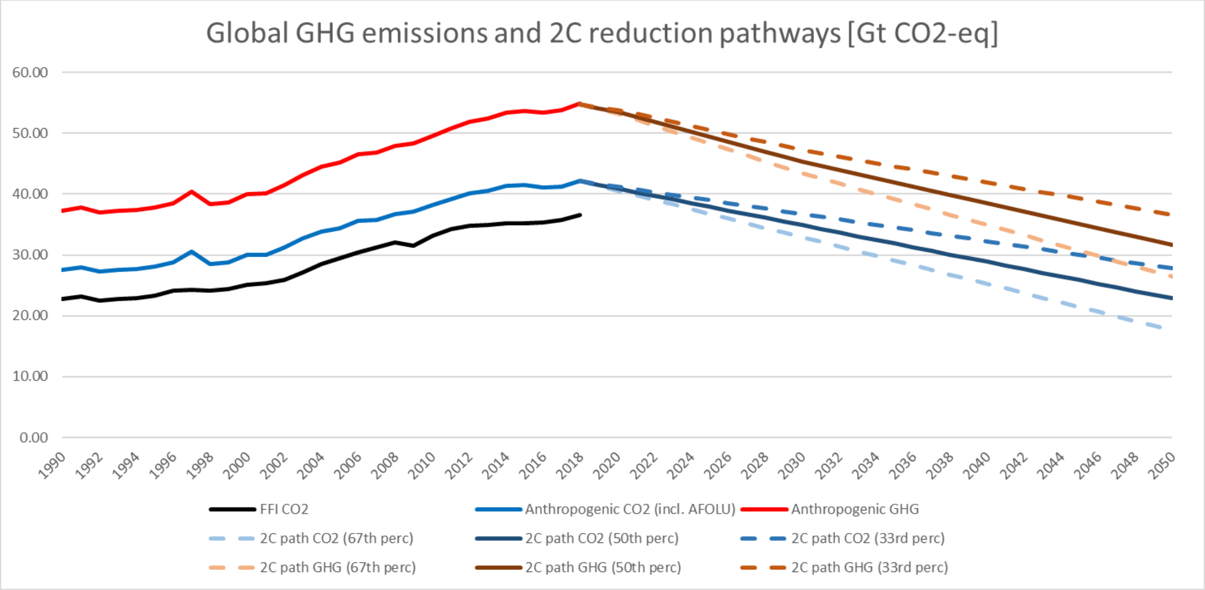

Figure 5: *Historical emissions of anthropogenic GHG (CO_2 from fossil fuel burning and industry, net anthropogenic CO_2 and aggregated GHGs) and reference pathways of net CO_2 and aggregated GHG emissions for 2 °C target. Dashed lines indicate uncertainty ranges due to uncertainty of adjusted CO_2 budget.*

***Table 5**: Characteristics of the reference emission pathways for the global warming targets of 1.5 °C and 2 °C. Non-CO_2 emissions are expressed in [Gt CO_2e] according to 100 years global warming potentials of CH_4 and N_2O given in (IPCC 2014, p. 212).*

Pathway		**1.5 °C**			**2 °C**		
Percentile		67th	**50th**	33rd	67th	**50th**	33rd
CO_2	Slope a [Gt CO_2 / year]	-2.11	**-1.53**	-1.06	-0.76	**-0.59**	-0.44
	Time of zero net τ_{ZN}	2037	**2045**	2057	2073	**2088**	2113
	Time of levelling out τ_L	2040	**2049**	2063	2089	After 2100	After 2100
	CO_2 emissions E_C at the time of levelling out [Gt CO_2]	-6.65	**-6.57**	-6.81	-12.13	Levelling out after 2100	Levelling out after 2100
	Net emissions in 2050 [Gt CO_2]	-6.65	**-6.57**	7.56	17.61	**22.85**	27.77
	2018-2050 cumulative emissions [Gt CO_2]	340	**570**	820	990	**1070**	1150
Non-CO_2	Emissions in 2050 [Gt CO_2e]	**6.49**			**8.83**		
	Emissions in 2100 [Gt CO_2e]	**6.19**			**8.68**		
	Cumulative emissions from 2018 to time of zero net CO_2 [Gt CO_2e]	190	**250**	330	540	**670**	Zero net CO_2 after 2100
	Cumulative emissions from time of zero net CO_2 to 2100 [Gt CO_2e]	410	**350**	270	240	**100**	Zero net CO_2 after 2100
	Cumulative emissions 2018-2050 [Gt CO_2e]	**290**			**340**		
	Cumulative emissions 2018-2100 [Gt CO_2e]	**610**			**780**		

It is important to point out that considerable discrepancies exist between our reference cumulative non-CO_2 emissions until the time of zero-net CO_2 emissions and reductions to TRCE-based carbon budgets needed to offset the non-CO_2 climate forcing. For the 1.5 °C reference pathway, the cumulative non-CO_2 emissions until $\tau_{ZN}(\Delta T)$ are 250 Gt CO_2-equivalent, while the carbon budget offset is estimated to be 310 Gt CO_2. For the 2 °C pathway this relationship is reverse, with 670 Gt CO_2-equivalent of cumulative non-CO_2 emissions vs. a 500 Gt CO_2 carbon budget offset. These discrepancies can be explained by: (1) methodological differences; (2) a short lifetime of CH_4; and (3) the different time horizons over which non-CO_2 emissions contribute to an increase in temperature. Indeed, benchmark CH_4 and N_2O emissions (cf. Tables 3 and 4) are derived as medians taken over 44 emission pathways belonging to the class "1.5 °C low OS" and 58 emission pathways constituting the class "Higher 2 °C", while offsets to carbon budgets are based on estimates of RNCTC derived by means of median regression over 205 scenarios in which net-zero CO_2 emissions are reached before 2100. Moreover, the short lifetime of methane together with the assumed benchmark methane emissions (cf. Table 3) imply that non-CO_2 radiative forcing peaks between 2030 and 2050 (see e.g., Rogelj *et al.* 2018, p. 120, Fig. 2.8.), thus requiring sharper initial reductions in CO_2 emissions to avoid or minimize the overshoot of the 1.5 °C warming target. On the other hand, in the case of the 2 °C pathway a large portion of non-CO_2 GHGs will be emitted in the second half of the 21st century. Their 100-year global warming potential will not fully play out before 2100, which is the time horizon within which the non-CO_2 contribution to a global temperature increase was analysed in SR15 to derive carbon budget offsets. This, for the 2 °C warming target, leads to the lower offset to carbon budget in relation to cumulative non-CO_2 emissions accounted in GWP-100 CO_2 equivalents.

2.4. Reference global GHG emission levels in 2050 and cumulative emissions until 2050 for 1.5 °C and 2 °C warming targets

Although anthropogenic GHG emissions already have a noticeable effect on Earth's climate, the full impact of these emissions will not be fully visible before the end of the 21st century and beyond. Yet, to avoid catastrophic levels of global warming, rapid decarbonization of the global economy within the next 2-3 decades is considered crucial, with the year 2050 believed to be the time until which the transition to a green (decarbonized) economy must be completed. The reference emission pathways discussed in the previous section are helpful to translate the long-term goals for climate stabilization to the time horizon of 2050.

Derivation of benchmark emissions in 2050 from our reference pathways is straightforward: these are the values the reference pathways reach in 2050. We divide them by the estimate of the size of global population[9] to obtain reference levels of per-capita emissions in 2050 that need to be reached to comply with the corresponding warming targets. Table 6 presents 2050 benchmarks for the 1.5 °C and 2 °C warming targets.

***Table 6**: Benchmark emissions in 2050 for the 50th percentile reference emission pathways corresponding to 1.5 °C and 2 °C warming targets. Per capita emissions are calculated using medium variant projections published by the UN Population Division.*

	CO_2		Aggregated GHG	
Target	Global [Mt CO_2]	Per cap [t CO_2/cap]	Global [Mt CO_2e]	Per cap [t CO_2e/cap]
1.5 °C	-6.57	-0.67	-0.08	-0.01
2 °C	22.85	2.35	31.69	3.25

Importantly, an emission pathway that reaches the benchmark in 2050 may still not be compatible with a given warming target if its shape significantly differs from the one of the reference emission pathway[10]. For that reason, it is important to complement benchmark emissions in 2050 with reference cumulative emissions until 2050, which can be easily computed as the area under the reference pathway up to 2050. Table 5 presents the reference cumulative emissions for period 2018-2050 for the 1.5 °C and 2 °C targets.

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[9] Here we use medium variant of estimate published by the UN Population Division (https://population.un.org/wpp/Download/Standard/Population/).

[10] For instance, an emissions trajectory which is always above the reference pathway and touches it only in 2050 (i.e. reaches the benchmark emissions in 2050) will result in higher cumulative GHG emissions and thus will lead to higher global temperature increase compared to that of the reference pathway.

3. Regional and national reference emission pathways and budgets

The reference emission pathways introduced above allow not only for scaling long-term mitigation goals (2100 and beyond) to shorter time horizons (like 2050). They also offer an easy and globally consistent way of downscaling global efforts required to mitigate climate change to regional or national levels. This global consistency allows for exploring a range of national or regional GHG emissions reduction targets that may be considered their fair contribution to global efforts aiming at mitigating global warming.

Our national/regional reference emission pathways are also independent of elaborate global socio-economic assumptions, like shared socio-economic pathways used in global-scale IAMs. That makes them convenient references for scenarios of green transition of local economies developed with help of small-scale modelling frameworks, for which climate change and developments of global economy are exogenous.

In this section we discuss how reference pathways and cumulative emission budgets can be derived from the global ones for regions, for example the EU, and for individual countries, in this case Austria. Furthermore, we show how these references could be used for assessing the consistency of various existing regional and national transformation scenarios with requirements for global mitigation actions needed to reach or limit global warming to 1.5 °C or 2 °C. This is important, since multiple studies of local scope build upon national or regional scenarios available in literature, but the consistency of these scenarios with global warming targets is often claimed without thorough argumentation.

3.1. Principles of splitting a pool of allowed global cumulative GHG emissions between countries or regions

To derive GHG emission budgets for a region or country that are in line with the warming targets of the Paris Agreement we distribute budgets of global GHG emissions (discussed in Section 2) between all nations in a top-down way. There are, however, multiple ways in which this could be done and, consequently, a pool of allowed emissions allowed for the region or country of interest will vary depending on a principle guiding such distribution.

A wide range of principle-based approaches to allocate GHG emission allowances to countries is available in the literature (Clarke *et al.* 2014, Raupach *et al.* 2014). As our aim is to derive robust budgets of national emissions that do not rely on subjective or uncertain assumptions, we do not consider principles like historical responsibility[11] or ability to pay[12]. Instead, we focus on principles that require only easily measurable or predictable quantities such as GHG emissions and population to determine national shares in the global pool of 2018-2050 cumulative GHG emissions compatible with 1.5 °C and 2 °C warming targets. Although many such

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[11] Historical responsibility takes into consideration not only current but also past GHG emissions and requires that the countries who profited from high levels of historical emissions bear higher burdens of climate change mitigation. However, the major practical drawback for this kind of principle is the need for specifying a point in time from which countries can be held responsible for their past emissions and consequent damages to climate. Such choice is a subjective decision of the modeler.

[12] According to this principle wealthier countries should reduce their emissions faster than poorer ones since implementing costly mitigation measures will cause less damage to welfare of their societies. Analysis of ability to pay is, however, based on uncertain relationships between costs of mitigation and welfare.

effort sharing principles are conceivable, we consider four principles below that span the range of shares in a global emissions budget that a country could claim with a certain fairness argument[13]:

1. **Proportionality to current population[14]:** the share of cumulative 2018-2050 GHG emissions is proportional to the fraction of the global population currently living in the region / country of question.
2. **Constant-rate convergence to globally equal per capita emissions in 2050[15]:** a region/country closes the gap between its per capita emissions and the global reference per capita emissions (i.e., emissions according to the reference emissions pathway divided by the projected population for each year) with a constant rate, with the gap being closed in 2050. More precisely, the pool B^i of emissions of country/region i is given by
$$B^i = \sum_{t=2018}^{2050} P_t^i \times \left(\frac{E_t}{P_t} + \left(\frac{E_{2018}^i}{P_{2018}^i} - \frac{E_{2018}}{P_{2018}} \right) \times \left(1 - \frac{t - 2018}{2050 - 2018} \right) \right)$$
where P_t^i and P_t denote the population of country/region i and the global population at time t, respectively, E_t stands for global emissions at time t according to a reference emissions pathway and E_{2018}^i are the emissions of country/region i in 2018.
3. **Proportionality to current territorial gross CO_2 emissions[16]:** the share of cumulative 2018-2050 GHG emissions is proportional to the ratio of gross CO_2 emissions emitted on the territory of the country/region in question to global gross CO_2 emissions in 2018.
4. **Proportionality to current territorial gross CO_2 emissions[17]:** the share of cumulative 2018-2050 GHG emissions is proportional to the ratio of gross CO_2 emissions embodied in the consumption of the country/region in question to the global gross CO_2 emissions in 2017.

3.2. Reference emission budgets and emission pathways for EU-28

We apply the above principles to assess the range of cumulative GHG emissions that can be allocated to the European Union. The results are gathered in Table 7.

The population of the EU-28 in 2018 was less than 7% of global population, which results in a relatively small share of the 2018-2050 emissions budget. Since current per-capita emissions in Europe are considerably above the global average, such a low emissions budget would require reaching per-capita emissions in 2050 below the global average. Such drastic emission cuts may be technically and politically unrealistic and thus the

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[13] The Paris Agreement does not rely on a single commonly agreed top-down principle of emission rights allocation. Instead, its mechanism is based on nationally determined contributions declared by individual countries. Each country, however, must explain how its emission reduction goal is a fair contribution to global efforts to mitigate climate change. Therefore, it is important for a country to understand what pool of emissions it can fairly claim.

[14] The fairness argument backing this approach is the principle that well-being of all people is equally important and thus everyone should enjoy the same allotment of emissions to provide for his/her well-being.

[15] The fairness argument backing this approach is similar to the one for proportionality to population but recognizes that current discrepancies in per capita emissions across the world will require some time to eliminate.

[16] High emitter countries / regions argue setting up their emission reduction targets in proportion to current emissions is their fair contribution to climate action since it is harder for high emitting economies to reduce their emissions in absolute terms.

[17] One may argue that emissions embodied in consumption are a proxy for the country's / region's welfare. Therefore, setting up emission targets in proportion to their current emissions from consumption can be considered fair since it implies proportional sacrifices in terms of welfare (regions of highest welfare will sacrifice most in absolute terms).

share of global emissions in proportion to the current population of the EU-28 marks the lower end of its emissions allowance for 2018-2050.

By the same token, the above-average GHG emissions of the EU-28 imply that a share of globally allowed cumulative emissions proportional to its current share in global (CO_2) emissions is the upper limit for the EU-28's budget of emissions until 2050. This is especially true if one uses as a reference the CO_2 emissions embodied in consumption.

The 2018-2050 emissions budget calculated according to the principle of constant-rate convergence to global per-capita emissions in 2050 is a good reference which is easily scalable, which allows some leeway to high-emitters yet acceptable on grounds of various fairness arguments. The reference emission pathways for the EU-28 based on this principle are depicted on Figure 6.

***Table 7**: Allowed cumulative emissions for the EU-28 for the period 2018-2050 compatible with the 1.5 °C and 2 °C warming targets, calculated based on different principles of allocating emission allowances. Emission budgets are based on 50th percentile reference pathways for global emissions and medium variant projections of population growth.*

Warming target	**1.5 °C**			**2 °C**		
Cumulative 2018-2050 emissions [Gt CO_2e]	**CO_2**	**Non-CO_2**	**GHG**	**CO_2**	**Non-CO_2**	**GHG**
Proportionality to current population	38	19	57	72	23	95
Constant-rate convergence of per capita emissions	41	17	57	69	20	88
Proportionality to territorial CO_2 emissions	53	27	80	101	32	133
Proportionality to consumption CO_2 emissions	67	34	102	127	41	168

We can use these reference emission pathways and their associated budgets of cumulative emissions until 2050 to assess how scenarios of transition to green economy on the scale of the EU-28 contribute to achieving the global warming targets of the Paris Agreement. We showcase this by way of example using the 1.5TECH and 1.5LIFE scenarios outlined in the report of the European Commission titled "A Clean Planet for All" (EC, 2018). Under these scenarios, the cumulative GHG emissions until 2050 are expected to be approximately 60 Gt CO_2e, which is 3 Gt CO_2 more than the reference budget for the EU-28 derived from the 50th percentile global reference pathway for the 1.5 °C target, assuming the medium projection variant of population growth and the constant-rate convergence to global equality of per-capita emissions in 2050. Cumulative non-CO_2 emissions can be as low as 12 Gt CO_2e emissions, 5 Gt CO_2e less than the reference budget. This is due to fewer options for non-CO_2 emission reductions implemented in the global scale IAMs – used to assess the global non-CO_2 budget, that underlays our reference budget for EU-28 – compared to models employed in the European Commission's report. On the other hand, the cumulative CO_2 emissions are 8 Gt CO_2 higher than the reference budget. This discrepancy is caused by the initial rates of CO_2 reductions being lower compared to the reference 1.5 °C pathway for the EU-28. In general, we conclude that the 1.5LIFE and 1.5TECH scenarios of the EU-28 to reach zero-net GHG emissions in 2050 is consistent with global efforts to keep global warming below 1.5 °C.

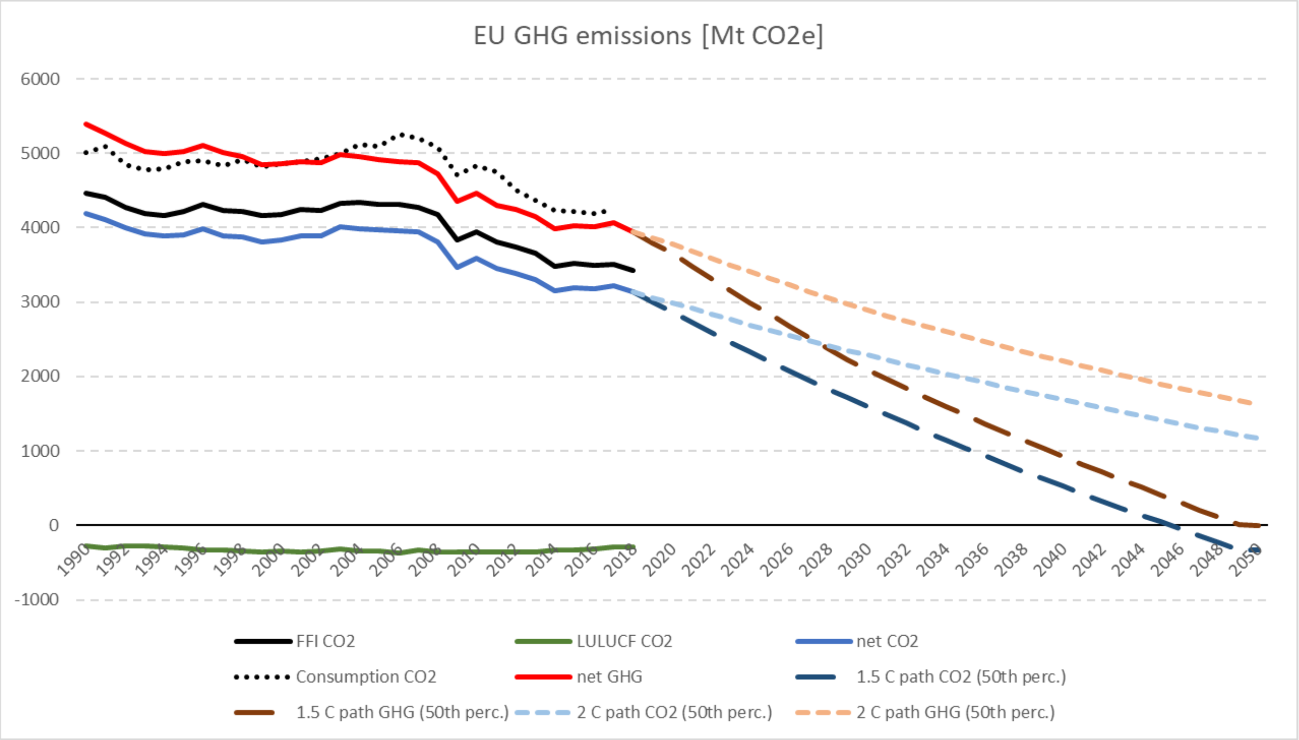

***Figure 4**: Historical GHG emissions of the EU-28 and reference emission pathways in accordance with the 1.5 °C and 2 °C warming targets, derived from the corresponding 50th percentile reference global emission pathways using the principle of constant-rate convergence of per capita emissions until 2050.*

3.3. Reference emission budgets and emission pathways for Austria

Reference pathways and budgets of emissions for the EU-28 region can be disaggregated further to national level using the same principles outlined in Section 3.1. Table 8 summarizes the results of such disaggregation for Austria. Similarly, as for the EU-28, reference budgets based on principles of proportionality to current CO_2 emissions – both territorial and embodied in consumption – are significantly less stringent in comparison with budgets proportional to the current population of Austria. Budgets based on the principle of constant-rate convergence to average per-capita emissions in 2050 fall in between. Figure 7 displays corresponding Austria's reference emission pathways for 1.5 °C and 2 °C targets.

We can use reference budgets from Table 8 to assess compatibility of scenarios of decarbonization of Austria's economy with the warming targets outlined in the Paris Agreement. As an example, we use the ref-NEKP scenario (Kirchengast *et al.* 2019), which would result in reaching net-GHG neutrality around 2045 with 1000 Mt CO_2e of cumulative net GHG emissions until 2050 (counting from 2017 onwards). This is in line with the very stringent 1.5 °C reference budget proportional to the current population of Austria.

***Table 8**: Austria's allowed cumulative emissions for the period 2018-2050 compatible with the 1.5 °C and 2 °C warming targets in accordance with different principles of allocating emission allowances. Emission budgets are based on 50th percentile reference pathways for global emissions and the medium projection variant of population growth.*

Warming target	**1.5 °C**			**2 °C**		
Cumulative 2018-2050 emissions [Mt CO_2e]	**CO_2**	**Non-CO_2**	**GHG**	**CO_2**	**Non-CO_2**	**GHG**
Proportionality to current population	660	339	999	1249	402	1650
Constant-rate convergence of per-capita emissions	836	268	1104	1345	322	1667
Proportionality to territorial CO_2 emissions	1033	531	1564	1955	629	2584
Proportionality to consumption CO_2 emissions	1496	768	2264	2831	911	3741

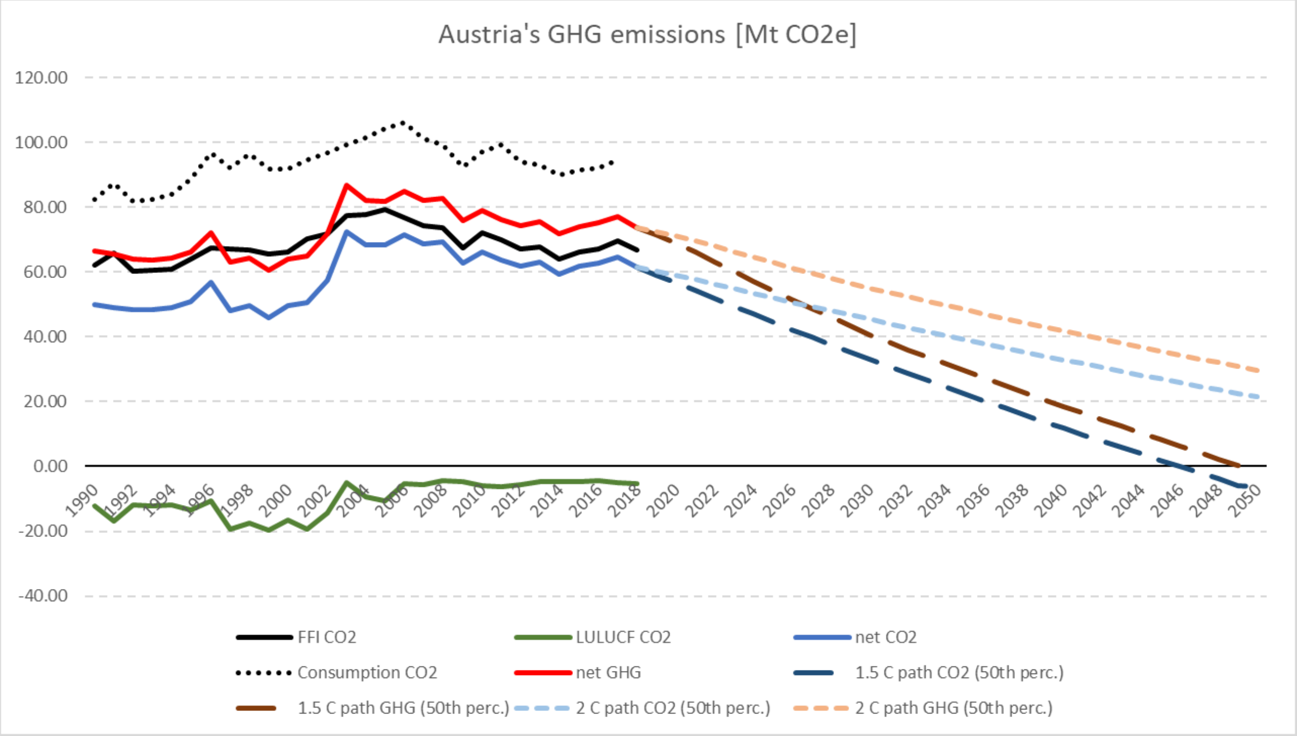

***Figure 5**: Austria's historical GHG emissions and reference emission pathways corresponding to 1.5 °C and 2 °C warming targets derived from 50th percentile global emission pathways using the principle of constant-rate convergence of per capita emissions in 2050.*

4. Summary and conclusions

In this paper we present a robust and globally consistent method of translating the planetary-scale targets of limiting the increase of global mean surface temperature into national budgets of cumulative GHG emissions until 2050, which provide benchmarks allowing to appraise compliance of transformation scenarios of national economies with the global warming targets.

Our approach is based on the concept of a GHG emissions budget which is considered a good predictor of future level of global warming. Despite some lingering uncertainties in the exact relationship between cumulative anthropogenic GHG emissions and the resulting increase of global temperature, this approach has two main advantages. First, global budgets of cumulative GHG emissions are concise representations of geophysical necessities that cannot be ignored or circumvented if the climate targets of the Paris Agreement are to be met. They are simple but not simplistic and are easy to communicate to decision-makers. Secondly, they are derived with help of observations and medium complexity climate models and do not rely on often opaque socio-economic assumptions and internal mechanisms of specific integrated assessment models. This makes them more difficult to question, on one hand, and compatible with any modelling framework, on the other hand. Finally, they are easily scalable, allowing to translate internationally agreed global warming targets of the Paris Agreement into limits on GHG emissions for local economies, both in terms of local emission budgets and the corresponding reference emission pathways.

This scalability is particularly important for setting up honest and realistic NDCs for individual countries. Current NDCs, even if fully implemented, fall short of the level of global GHG emission reductions necessary to meet the goals of the Paris Agreement (UNFCCC 2016) and it is unrealistic to expect that without some coordination mechanism individually determined national contributions will turn out to be adequate. As an alternative to common agreement on sharing the burdens of climate action – which international community failed to achieve for several decades – Meinshausen *et al.* (2015) propose a leadership scheme in which one of the main emitters set up the pace for emission reductions that is matched by other countries according to burden-sharing principles of their choice. In absence of such leadership or alternative mechanism, global consistency of national GHG emission budgets proposed in this paper alleviates to some extent the lack of international coordination, making these national budgets reliable foundations for designing national climate policies that are in line with goals of the Paris Agreement. We allocate shares of global GHG emissions budgets to countries according to several burden sharing schemes available in the literature. Even if none of these schemes is likely to be commonly accepted, this exercise allows us to assess the ranges of cumulative emissions available for each individual country in context of warming targets of the Paris Agreement.

Global budgets of GHG emissions are not only easily scalable down to the level of individual countries. The corresponding reference emission pathways allow for easy scaling them in time. By integrating the area under the reference pathway over certain time interval one immediately obtains an estimate of an emissions budget for that period. Moreover, a reference emission pathway provides a benchmark emission target for any specific moment in future (e.g., for 2050). Benchmark emissions are abundant in literature, but these are typically derived with the help of integrated assessment models and for specific scenarios or classes of scenarios of global climate mitigation action (see e.g., Rogelj *et al.* 2018, p. 119, Table 2.6). In contrast, benchmark derived from a budget of allowed GHG emissions through a corresponding reference emission pathway reflect sine-qua-non conditions, rather than the consequences of specific (often socio-economic) assumptions of a global-scale scenario of climate change mitigation. Importantly, a reference emission pathway should not be interpreted as projected trajectory of GHG emissions for any specific scenario. Rather, true to its name, it should be regarded as a reference against which the progress towards desired warming target can be appraised, with an understanding that actual emissions above the pathway will have to be compensated by even sharper emission reductions down the line.

Cumulative GHG emission budgets and the corresponding reference emission pathways proposed in this paper are also useful tools in modelling practice. As already mentioned, they do not rely on any specific socio-economic assumptions or set-ups of particular integrated assessment models, and thus are compatible with virtually any modelling framework, to which they can serve as guardrails. For instance, our emission budgets can serve as hard constraints in optimization models which resolve for GHG emissions. Alternatively, they can be used to assess alignment of a specific scenario with a given warming target – an application which we demonstrated in Section 3 with the case examples of transformation scenarios for EU and Austria. Finally, with help of scenarios covering all anthropogenic GHG emissions, consistency of which with a desired warming target has been established, it is possible to specify emissions budgets for individual sectors of economy, which then can serve as constraints for sector-specific models. For example, one could take cumulative GHG emissions from Forestry and Agriculture sectors under the 1.5LIFE scenario of EU-wide economic transformation (alignment of which with the 1.5 °C target we have verified in Section 3.2) and subtract them form the 1.5 °C budget that we derived for the EU bloc, and thus arrive at an estimate of allowed cumulative GHG emissions for EU's Energy, Industry and Waste sectors. This budget of GHG emissions downscaled to abovementioned sectors can then serve as a constraint for an EU-wide sector-specific model covering only sectors of Energy, Industry and Waste.

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